Abstract

The present thesis reports, research works done by the author (in collaboration with a few others) to probe various aspects of cosmic rays related to their origin through high energy gamma rays and neutrinos. The main objectives of the works are

i) to review the present status of gamma ray and neutrino astronomy regarding cosmic ray origin,

ii) to examine the spectral behavior of produced gamma rays and the conversion efficiency in a few supernova remnants (SNRs) and to explore the consequences of the maximum attainable energy of cosmic rays in SNR as Z times the knee energy, where Z is the atomic number, as may be achievable under amplified magnetic field scenarios, on the secondary gamma-ray spectrum of young SNRs,

ii) to investigate theoretically the implication of maximum attainable energy of cosmic rays to PeV energies in supernova remnants on high energy gamma rays and neutrinos from molecular clouds proximity to the SNR and whether ongoing/near future experiments of gamma rays/neutrinos can resolve the maximum energy issue or not by observing high energy gamma rays/neutrinos from molecular clouds around the SNR,

iii) to analyze the fluxes of high energy gamma rays and neutrinos produced in interaction of high energy cosmic rays with solar radiation and coronal matter as a cosmic ray mass spectrometric technique,

and

iv) to critically examine the conventional idea that high energy neutrinos are dominantly originated only in hadronic processes by comparing the flux of leptonic originated and hadronic originated high energy neutrinos from a viable cosmic ray source,

It is widely believed that Galactic cosmic rays are originated in SNRs, where they are accelerated by a diffusive shock acceleration (DSA) process in supernova blast

waves driven by expanding SNRs. In recent theoretical developments of the DSA theory in SNRs, protons are expected to accelerate in SNRs at least up to the knee energy. If SNRs are the true generators of cosmic rays, they should accelerate not only protons but also heavier nuclei with the right proportions, and the maximum energy of the heavier nuclei should be the atomic number (Z) times the mass of the proton.
We investigate the implications of the acceleration of heavier nuclei in SNRs on energetic gamma rays produced in the hadronic interaction of cosmic rays with ambient matter. Our findings suggest that the energy conversion efficiency has to be nearly double for the mixed cosmic ray composition compared to that of pure protons to explain observations. One of the key unsettled issue in SNR origin of cosmic rays model is the maximum attainable energy by a cosmic ray particle in the supernova shock. Recently it has been suggested that an amplification of effective magnetic field strength at the shock may take place in young SNRs due to growth of magnetic waves induced by accelerated cosmic rays and as a result the maximum energy achieved by cosmic rays in SNR may reach the knee energy instead of $\sim$ 200 TeV as predicted earlier under normal magnetic field situation. We find that the gamma-ray flux above a few tens of TeV would be significantly higher if cosmic ray particles could attain energies Z times the knee energy in lieu of 200 TeV. The two stated maximum energy paradigms will be discriminated in the future by upcoming gamma-ray experiments like the Cherenkov Telescope Array (CTA).

In chapter 3 we investigate the implication of such maximum energy scenarios on TeV gamma rays and neutrino fluxes from the four molecular clouds interacting with the SNR W28. Our findings suggest that upcoming gamma-ray experiments like the Large High Altitude Air Shower Observatory (LHAASO) and the CTA should be able to settle the issue of the maximum energy of cosmic rays in SNRs observationally. The estimated neutrino fluxes from the molecular clouds is, however, out of reach of the present generation of neutrino telescopes.

In chapter 4 we explore the possibility of estimating the mass composition of primary cosmic rays above the knee of their energy spectrum through the study of high-energy gamma rays, muons, and neutrinos produced in the interactions of cosmic rays with solar ambient matter and radiation. It is found that the theoretical fluxes of TeV gamma rays, muons, and neutrinos from a region around 15^o *of the Sun are sensitive to a mass composition of cosmic rays in the PeV* *energy range. The experimental prospects for the detection of such TeV gamma rays/neutrinos by future experiments are discussed.*

Finally we demonstrate that TeV neutrinos can also be originated from energetic electrons via electromagnetic interactions in different potential cosmic ray sources with flux levels comparable to the hadronic originated neutrinos at high energies. A notable signature of leptonic origin is the presence of a spectral break in the energy spectrum of so produced neutrinos below which the flux decreases sharply whereas above the break energy the spectrum will be flatter relative to cosmic ray spectrum. For unambiguous identification of sites of hadronic cosmic rays it is therefore necessary to measure the energy spectrum of TeV neutrinos over a wide energy range. In contrast, the energy spectrum of TeV gamma rays generated from energetic electrons via inverse Compton scattering will become steeper as one approaches to higher energies. A combine detection of TeV gamma rays and neutrinos with appropriate fluxes and spectral pattern from astrophysical objects will thus provide a better opportunity for conclusive identification of the nature of their origin, hadronic or leptonic.

The material/results reported in this thesis have been published in different journals/proceedings as shown below

1. *"Implications of supernova remnant origin model of galactic cosmic rays on gamma rays from young supernova remnants"*, Prabir Banik and Arunava Bhadra, Physical Review D 95, 123014 (2017), DOI: 10.1103/PhysRevD.95.123014.

2. *"Probing maximum energy of cosmic rays in SNR through TeV gamma rays and neutrinos from the molecular clouds around SNR W28"*, Prabir Banik and Arunava Bhadra, communicated for publication.

3. *"Probing the cosmic ray mass composition in the knee region through TeV secondary particle fluxes from solar surroundings"*, Prabir Banik, Biplab Bijay, Samir K. Sarkar, and Arunava Bhadra, Physical Review D 95, 063014 (2017), DOI: 10.1103/PhysRevD.95.063014.

4. *"High energy leptonic originated neutrinos from astrophysical objects"*, Arunava Bhadra and Prabir Banik, communicated for publication.

5. *"The knee in the cosmic ray energy spectrum from the simultaneous EAS charged particles and muon density spectra"*, Biplab Bijay, Prabir Banik, Arunava Bhadra,

Astrophys Space Sci (2016) 361:311, DOI 10.1007/s10509-016-2897-7 (not included in the thesis).

6. *"Characteristics of transonic spherical symmetric accretion flow in Schwarzschild-de Sitter and Schwarzschild anti-de Sitter backgrounds, in pseudo-general relativistic paradigm"*, Shubhrangshu Ghosh and Prabir Banik, International Journal of Modern Physics D, Vol. 24, No. 11 (2015) 1550084, DOI: 10.1142/S0218271815500844 (not included in the thesis).